Chapter 65
Probability and Integration Judgment Based Best Selection of Aircraft Conceptual/Preliminary Scheme

Kang-wen Sun and Jun Huang

Abstract The technical feasibility analysis of an aircraft design scheme directly influences the design proposal, which determines whether scheme can satisfy the maximum design requirements or we can continue the detailed design. Conventional design evaluation of a new technical influence is insufficient, because the weight evaluation (analytic hierarchy process, AHP) is usually subjective. This paper proposes a new impact analysis method based on probability theory, and the comprehensive information including the data envelopment analysis (DEA) and the interval number AHP is referred to as a comprehensive empowerment of the appraisal criterion. According to the proposed method, the best selection method of an aircraft conceptual/preliminary scheme based on probability and integration judgment is established. Finally, some examples are presented to demonstrate the validity of the method.

Keywords Probability • Integration judgment • The technical feasibility of aircraft design scheme • Best selection

Introduction

Along with the improving requirements of various applications, modern aircraft design becomes more and more complicated (Jianxi Xie et al. 2004; Wen Xiong 2005). Due to the lack of consideration of the influence degree of a new technology as well as the use of analytic hierarchy process (AHP) of subjective values, the traditional empirical formula and qualitative analysis technology based aircraft conceptual/preliminary scheme evaluation method hardly meets the design need of the modern aircraft. Probability theory is employed in this paper to analyze feasibility of new technology (DeLaurentis Daniel and Mavris 2002; Kirby 2001; Mavris and

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Delaurentis 2003), This method needs not to know the influences of these new technology characteristics, and instead enhances the design scheme evaluation of anti-interference ability by using interval number AHP (Jianjun Zhu 2005; Zhen Wang and Mao Liu 2006) and data envelopment analysis (DEA, an objective weight method) (Yemei Wang 2008; Yang Han et al. 2010) combined with the comprehensive empowerment method to improve the weight factor of objective reality.

According to the above technique, this paper presents a best selection method of an aircraft conceptual/preliminary scheme based on probability and integration judgment, which can be applied to the technical feasibility analysis of the multiple design schemes and the best design scheme selection.

The Impact Analysis of New Technology Based on Probability

The development of a new technology is a gradual process. The new technology development can be divided into ten steps, which are shown in Table 65.1. According to one point system's grading principle, each step is endowed with a corresponding grade value. Then, a certain number of experts are invited to evaluate every technical development stage.

The experts finished independently evaluation of the principles in Table 65.1 (Kirby 2001). The decision-making departments get the maturity probability of these new technologies during the application period using the following formula:

$$(P_{WB})_I = \sum_{j=1}^{n} \left(G_j \times \frac{M_j}{M} \times 100\% \right) \tag{65.1}$$

Where G_j denotes the technical completeness grade of the new technology under application stage, M denotes the number of experts, and M_j denotes the number of experts who recognize the application technology in the state of grade G_j.

When the new technology becomes applicable, combining the modeling software simulation with the experimental validation is adopted to get the impact data about the intermediate variables in the design analysis. In addition, in consideration of the development stage of the new technology, the impact data can be expressed by using interval number method. Based on the comprehensive analysis, the integration impact factor of the new technology on the i^{th} design criterion (or target) can be expressed as:

$$P_{JKi} = \left[\sum \left((P_{SY})_{Ii} \cdot (P_{WB})_I \right) + \sum \left((P_{SS})_{Ji} / (P_{WB})_J \right) \right] \tag{65.2}$$

where $(P_{SY})_{Ii}$ denotes the income of the I^{th} new technology brought by the i^{th} criterion, $(P_{SS})_{Ji}$ denotes the loss of the J^{th} new technology brought by the i^{th} criterion, $(P_{WB})_I$ and $(P_{WB})_J$ denote the technical mature probability of the new

Table 65.1 The new technology readiness levels (TRL)

Stage description	Level	Work to do	Grading criteria
Basic research	1	Report and comment on basic scientific/engineering principles	0.1
Feasibility research I	2	Clearly demonstrate the technology concept, application, and potential benefits (select candidate system)	0.2
Feasibility research II	3	Prove the concept of technology analytically and/or experimentally (proof of critical functions or characteristics)	0.3
Technology development I	4	Study the system concept in laboratory (breadboard test)	0.4
Technology development II	5	Validate the system concept and its potential benefits in a controlled circumstance	0.5
System development I	6	Demonstrate system concept prototype in a relevant circumstance	0.6
System development II	7	Validate system prototype and potential benefits in a more broadly circumstance	0.7
Operational verification I	8	Construct and demonstrate actual system in a relevant circumstance, and substantiate its benefits	0.8
Operational verification II	9	Operate the actual system and substantiate its benefits	0.9
Technical maturation	10	Extensive application after various validation and improvement	1

technology in the future operational stage. The Eq. (65.2) carries on division processing to the loss factor, mainly due to the immaturity of the new technology, which brings a bigger loss to the system. Therefore, the policymaker must be discrete when the selection of the new technology may cause a potential lose.

Comprehensive Empowerment Method Based on Integration Judgment

At present, the determination methods of the relative weight factor mainly include the subjective weight method and the objective weight method. The objective weight method based on the actual data of all criteria, employs the mathematical model with various standards to get weight coefficient. But this method however cannot reflect the preference of decision maker. Since the weight coefficient may not be consistent, this will give rise to a discrepancy for the final decision (Zeshui Xu 2004). In subjective weight method, the policymaker chooses criterion weight coefficient according to their fancy, experience and knowledge, or uses a mathematical model to determine the weight coefficient, based on comparative matrix after the binary comparison among all criteria. But the disadvantage of this method will introduce a subjective factor that may exert a strong influence on the result which may depart from object reality (Choo and Wedley 2004). In order to make the final decision more objective and reliable, dual considerations are paid to the fancy of the policymaker in criteria and reduce the arbitrariness in criteria weight determination. Through the interval number AHP, the subjective weight coefficient is obtained, which reflects the policymaker's subjective fancy. Through the DEA we can get the objective weight coefficient, which can reflect the objective relationship between two discretional criteria (or attributes). Finally, by linear weight method one can acquire the evaluation criteria of synthesis weights, namely:

$$w^* = \alpha\bar{\varpi} + (1 - \alpha)\xi \tag{65.3}$$

where w^* is the synthesis weight; $\overline{\varpi}$ is the subjective weight decided by the interval number AHP; ξ is the objective weight decided by the DEA, $\alpha \in [0,1]$ is the subjective fancy coefficient, $(1-\alpha)$ is the objective fancy coefficient, and α usually takes 0.5. To facilitate the problem analysis, it is noteworthy of getting an average value from the analysis result in which the interval number AHP contains. Furthermore, the comprehensive weight that is obtained from the interval number AHP and the DEA should be normalized.

Steps as follow should be implemented to ascertain relative criteria weight number in the aircraft design:

- According to the analysis of the client demand, confirm the objective sets that satisfy the performance index (i.e. the performance index and its number n).
- Based on the demand of client, invite a number of k experts in relative fields to give an evaluation for the performance indexes mentioned above.
- Establish a judgment matrix B_{nxn} based on the results given by experts:

$$B_{n\times n} = \begin{bmatrix} [b_{11}^L, b_{11}^U] & [b_{12}^L, b_{12}^U] & \cdots & \cdots & [b_{1n}^L, b_{1n}^U] \\ [b_{21}^L, b_{21}^U] & [b_{22}^L, b_{22}^U] & \cdots & \cdots & [b_{2n}^L, b_{2n}^U] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ [b_{n1}^L, b_{n1}^U] & [b_{n1}^L, b_{n1}^U] & \cdots & \cdots & [b_{nn}^L, b_{nn}^U] \end{bmatrix} \tag{65.4}$$

- Analyze the partial uniformity of the interval number judgment matrix B_{nxn} and the uniformity extent. If the interval number judgment matrix B_{nxn} is not partially uniform or its uniformity extent is not strong enough, a modification is needed.
- After the interval number judgment matrix B_{nxn} meets uniformity requirement, obtain the subjective weight number $\overline{\varpi}$ by using the genetic algorithm.
- Calculate the objective weight ξ by using nonlinear programming software, such as Lingo 7.0.
- Solve Eq. (65.3) to get the final comprehensive weight.

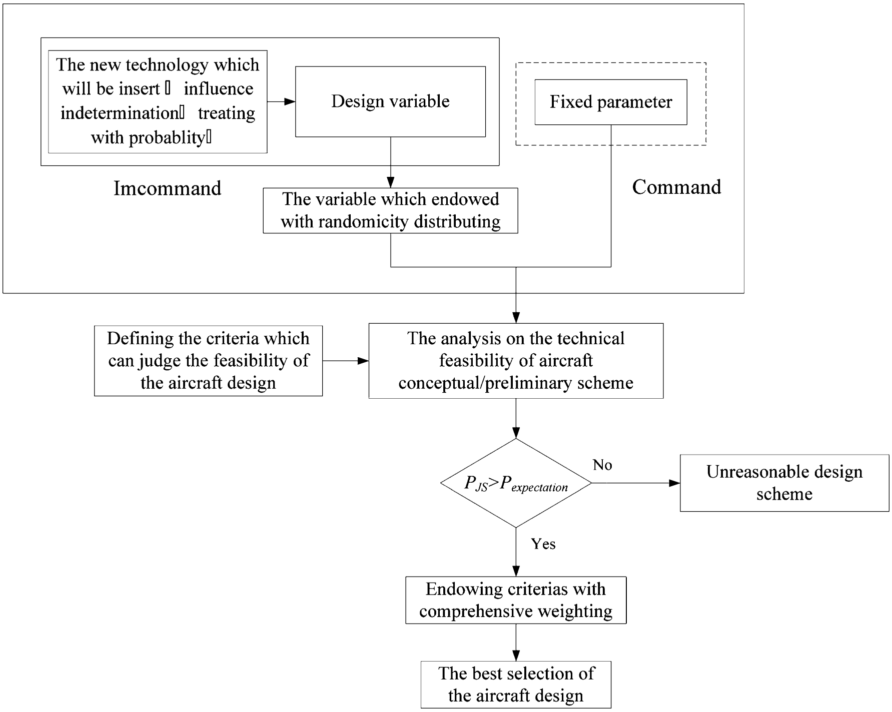

Fig. 65.1 The flow chart of the best selection method of aircraft conceptual/preliminary scheme based on probability and integration judgment

The Best Selection Method of Aircraft Design Scheme

Based on the new technology influence characteristic analysis method combined with the interval number AHP and DEA comprehensive weight method, the best selection method of an aircraft design scheme is constructed, as shown in Fig. 65.1:

- According to the domain of the design variable and the influence of the new technology exerted on the correlated variables shown in Fig. 65.1, the corresponding design variables are designated with a random distribution.
- For a specific aircraft, an accurate model based on the experiential formula (referred to (Raymer 1999) for the related parameters and formula) is selected. The technical feasibility analysis of aircraft conceptual/preliminary scheme is expressed as:

$$P_{JS} = P\{\cap[F_{i\min} \le f_i(x, y) \cdot P_{JKi} \le F_{i\max}]\} \quad (i = 1, 2, \ldots M) \tag{65.5}$$

where P_{JS} denotes the technical feasibility of an aircraft conceptual/ preliminary scheme. The items in square brackets at the right side of Eq. (65.5) denotes the probability of the ith design criterion actual value and the corresponding design requirements $F_i \in (F_{imin}, F_{imax})$ under the condition of the effective design value, x is the design variable vector, and y is the state variable vector. Generally, when feasible probability is larger than 50%, this design scheme is ideal, and otherwise the design scheme is unreasonable.

- When the feasibility of design scheme meets the general requirements, use the comprehensive weight method in part II to analyze the comprehensive weight of the related design target.
- Based on the preceding analysis, the best selection of the design scheme is obtained by using the equation as follows:

$$P_{JSE} = P\left\{\cap\left[(w_i \cdot M) \cdot F_{i\min} \le f_i(x,y) \cdot P_{JKi} \le \frac{F_{i\max}}{(w_i \cdot M)}\right]\right\} \quad (i = 1, 2, \ldots M) \tag{65.6}$$

Where P_{JSE} denotes the equipollence technical feasibility of the alternative scheme, w_i is the ith design criterion weight number, and M is the appraisal criterion number. The item in square brackets at the right side of Eq. (65.6) denotes the probability of the ith actual design criterion value and the corresponding design requirements $F_i \in ((w_i \cdot M) \cdot F_{imin}, F_{imax}/(w_i \cdot M))$ under the condition of taking the effective design the value. To emphasize the weight number reasonable adjustments of transition coefficient $(w_i \cdot M)$ to the relatively feasible domain of criterion are performed. Evaluation criterion must be satisfied harshly.

One of the alternative schemes that meets the requirement of the specified P_{JSE}, P_{JSE} with highest value is the best solution. If no alternative schemes' P_{JSE} values were larger than 0, the related criterion value must be readjusted to get higher P_{JSE} value. Correspondingly, if several alternative schemes' P_{JSE} values reach 1, the related criterion value should be modified to reduce P_{JSE} value. Thus, all alternative schemes can be distinguished and the truly preferred scheme can be obtained finally.

Instance Analysis and Validation

Select the initial design indexes of a certain aircraft (refer to the third generation aircraft) as shown in Table 65.2, and the domain of relevant design variables are shown in Table 65.3. Some relevant fixed parameters setting can be referred to (Weiji Li 2003).

Let A and B denote two designing departments. They select the new technical program permutation in their own design schemes respectively: A {T1, T2, T3}, B {T4, T5, T6}. And the specification is shown in Table 65.4 (Aditya Utturwar et al. 2002).

Table 65.2 Request of target

Design property	Guide line
Takeoff gross weight (W_{dg})	$\leq$24,000 kg
Takeoff field length (S_{TOFL})	$\leq$500 m
Approach speed (V_{app})	$\leq$70 m/s

Table 65.3 Design variables

Design variable	Min	Max
Wing aspect ratio (A_w)	3	7
Wing area (S_w/m^2)	40	80
Wing sweep ($\Lambda_w/°$)	35	60
Wing maximum thickness-to-chord ratio ($(t/c)_w$)	0.03	0.07
Horizontal tail aspect ratio (A_{HT})	6	9
Horizontal tail area (S_{HT} /m^2)	12	17
Horizontal tail sweep ($\Lambda_{HT}/°$)	30	50
Vertical tail aspect ratio (A_{HT})	6	10
Vertical tail area (S_{VT} $/m^2$)	12	18
Vertical tail sweep ($\Lambda_{VT}/°$)	40	60
Max flying speed (Ma)	2.0	2.5
Thrust-to-weight ratio (T/W)	0.9	1.2
Air density at cruise height ($\rho_c/kg/m^3$)	0.104	0.365

Table 65.4 New technical detailed list

Designing department	Technical symbol	The definition of the technical
A	T1	Active load alleviation on tail
	T2	Integrative antenna systems
	T3	Biologically inspired material systems on fuselage structure
B	T4	Low cost composite manufacturing on tail structure
	T5	Propulsion system health management
	T6	BIOSANT on wing structure

The New Technology Impact Analysis

Assuming the new technology must be applied in 2015, through the synthesis judgment from 30 peer experts, the new technical TRL statistical table is shown in Table 65.5. To facilitate our analysis, the data are fitted referring to the literature (Kirby 2001) based on a different normal distribution. Furthermore, in view of both simulation results- and the relevant test data for validation, the impact on the relevant intermediate parameters caused by the new technology is shown in Table 65.6.

Table 65.5 The new technical TRL statistical table

Grading technical	0.5	0.6	0.7	0.8	0.9	1	PWB
T1	–	4	4	10	9	3	0.81
T2	–	4	8	10	8	–	0.75
T3	3	5	10	10	2	–	0.71
T4	–	–	3	4	14	9	0.9
T5	–	–	2	6	11	11	0.9
T6	1	4	13	10	2	–	0.73

Table 65.6 Technical influence matrix

		New technical group					
% k_i		T1	T2	T3	T4	T5	T6
k_1	Wing weight	–	–	–	–	–	−2
k_2	Fuselage weight	−5	–	−13	–	–	–
k_3	Vertical tail weight	−5	–	–	−20	–	–
k_4	Horizontal tail weight	–	–	–	−20	–	–
k_6	Electrical weight	2	−45	–	–	–	–
k_7	Engine weight	–	–	–	–	5	–
k_8	Zero drag	–	1	–	–	–	–
k_9	Fuel cost	–	–	–	–	−4	–
k_{10}	Thrust-to-weight	–	–	5	–	–	5

Comprehensive Weight Analysis

Assume the interval number judgment matrix of the experts' evaluation is $B_{3\times 3} = \begin{bmatrix} [1,1] & [3,4] & [5,7] \\ [\frac{1}{4},\frac{1}{3}] & [1,1] & [2,3] \\ [\frac{1}{7},\frac{1}{5}] & [\frac{1}{3},\frac{1}{2}] & [1,1] \end{bmatrix}$.

The random deterministic judgment matrix is $A = \begin{bmatrix} 1 & 4 & 7 \\ \frac{1}{4} & 1 & 3 \\ \frac{1}{7} & \frac{1}{3} & 1 \end{bmatrix}$. Then the consistency index can be obtained as $C.I. = \frac{\lambda_{\max} - n}{n-1} = 0.0324$.

By searching the corresponding stochastic consistency index table (as shown in Table 65.7) we know R.I. = 0.52, and therefore the above matrix uniform proportion is CR(A) = 0.0324/0.52 = 0.06 <0.1, which demonstrates that the local uniform degree of the above interval number judgment matrix is satisfactory. In addition, the degree of the N (= 100) judgment matrices generated randomly by aforementioned interval number judgment matrix is $\delta = 68\% > 60\%$, which shows the degree of the interval number judgment matrix is consistent.

Employ GA method and MATLAB 7.0. Assume the population N is 30, the crossover probability P_c is 0.9, mutation probability P_m is 0.001, and the crossover operation parameter α is 0.3. Thus, relative weights of the three performance indices (i.e. W_{dg}, $S_{TO/LFL}$, V_{app}) are $\overline{w_1} = [0.9161, 0.9471]$, $\overline{w_2} = [0.2769, 0.3715]$, and $\overline{w_2} = [0.1252, 0.1620]$, respectively, which can be used to calculate the subjective weights of the three performance indexes, i.e., $\overline{w_1^*} = 0.9316$, $\overline{w_2^*} = 0.3242$, $\overline{w_3^*} = 0.1436$.

Table 65.7 The stochastic consistency index table

n	1	2	3	4	5	6	7	8
R.I.	0	0	0.52	0.89	1.12	1.26	1.36	1.41

Through Lingo7.0, the objective weights of the three performance indices are respectively $\xi_1 = 0.604$, $\xi_2 = 0.257$ and $\xi_3 = 0.139$. Therefore, the comprehensive weights of the three kinds of performance indices are respectively ($a = 0.5$ here) 0.7678, 0.2906, and 0.1413. After normalized processing the comprehensive weights of the three performance indices are $w_1* = 0.6400$, $w_2* = 0.2422$, and $w_3* = 0.1178$, respectively.

Through the above analysis, the feasibility evaluation mathematical model of the design scheme candidates can be expressed as follows:

$$P_{JSE} = P\left(0 \leq W_{dg} \leqslant \frac{23,600}{1.92}, 0 \leqslant S_{TOFL} \leq \frac{500}{0.7266}, 0 \leq V_{app} \leq \frac{65}{0.3534}\right)$$

According to the preceding formula, combining the influence matrix in Table 65.7 with the feasibility analysis program, the following result can be obtained

$$(P_{JSE})_A = 0\%, \ (P_{JSE})_B = 0\%.$$

Consequently, the best selection result is unable to carry on temporarily, and the values of the related constraint criterion must be adjusted.

In view of the above analysis, the weight processing on W_{dg}, makes the constraint excessively strict, and therefore value of the W_{dg} criterion must be adjusted. After the constraint criterion W_{dg} coefficients are relaxed by 1.85, the following formula can be obtained:

$$P_{JSE} = P\left(0 \leq W_{dg} \leq \frac{23600 \times 1.85}{1.92}, 0 \leq S_{TOFL} \leq \frac{500}{0.7266}, 0 \leq V_{app} \leq \frac{65}{0.3534}\right)$$

By recalculating, $(P_{JSE})_A = 0\%$, $(P_{JSE})_B = 16\%$ is obtained. Therefore, according to the application requirements of the users, the technical feasibility of design scheme B is better than that of A, namely, project B is a better solution. Furthermore, according to Eq. (65.5), $(P_{JS})_A = 89.5\%$, $(P_{JS})_B = 97.9\%$, which can also verify that the technical feasibility of design scheme B is better than that of A.

Conclusion

This paper analyzes the degree of a new technology development and its impact on the design scheme using probability theory. And then, a comprehensive weight analysis by combining the subjective weight method (i.e. the interval number AHP) with the objective weight method (i.e. DEA) is proposed. In view of the above two aspects, the best selection method of aircraft conceptual/preliminary scheme based on probability and integration judgment is established. This method fundamentally overcomes the appraisal flaws of the traditional design scheme, such as insufficient consideration on new technical influence, subjective inclination on weight evaluation. And thus precision of the appraisal result is improved.

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